FORTY YEARS' STUDY OF SNOW CRYSTALS

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By WILSON A. BENTLEY

[Jericho, Vt., December, 1923]

It is, perhaps, common knowledge that the writer has carried on for many years photographic studies of snow crystals and of other forms of water.

My great good fortune in being permitted to enter this fascinating field of endeavor was doubtless due to the fact that my mother placed a microscope at my disposal while I was about midway in my teens. In the search for interesting microscopic objects I soon learned of the marvelous beauty of the snow crystals. Amazed and thrilled at their matchless loveliness, I began a systematic study of them, at first by visual observation and drawings (1882–1884), later by photomicrographs. Assisted by indulgent parents I procured, in 1884, a photomicroscopic camera and secured my first photomicrographs of snow crystals in December, 1884, when in my nineteenth year.

The work soon became so all-absorbing that I have continued it with undiminished enthusiasm all these years. No words can convey the least idea of the intense enjoyment, the almost countless thrills, these winter studies have afforded me. As is usually the case in scientific endeavors the work has not proved remunerative financially. Indeed, it has made it necessary for me to practice much self-denial that I might pursue it. Yet, it has repaid me a thousand-fold in the enjoyment I and others have derived from it, and in the satisfaction of having contributed a little to the world's knowledge, and of having, perhaps, erected a permanent memorial to my life's labors.

The marvelous beauty of the snow crystals has become common knowledge through the publication of photographs of them in many of the world's magazines, periodicals, and books. Articles by the writer and others, published in the MONTHLY WEATHER REVIEW, have served to convey to its readers an idea of their wondrous beauty, symmetry, and complexity, and to give much information regarding them. This year (1923) has seen the publication in Poland by A. Dobrowski of "Belgica" fame, a splendid and most ambitious work on snow crystals and other forms of water, entitled "Historja Naturalna Lodu." It is profusely illustrated, and includes about 100 reproductions of the writer's photomicrographs.

The present article, while giving a brief review of our work and some additional data, will confine itself mainly to a portrayal of some of the more remarkable forms secured and some interesting phenomena in connection therewith.

The winters have varied greatly as regards the character of their snowfalls, the number of favorable ones, etc. New sets of photomicrographs, numbering from about 100 up to 300, have been secured each winter (except the winter of 1913–14) until now my collection numbers 4,200, no two crystals being alike. Singularly enough, the winter of 1913–14, noted for the lack of sunspots on the sun, and auroras, furnished but few good crystals.

The more recent observations have amply confirmed many of the earlier theories and conclusions, among others, that the majority of the more perfect tabular snow crystals occur within the western quadrant of general storms, or within regions of snowfall lying between two closely lying "lows." As might be expected, the best crystals do not occur, as a rule, during the most intense snowfalls, or during extremely low barometer readings, but during medium or somewhat scanty snowfall, when the barometer indicates a pressure of from 29.7 to 30.2 inches.

Among the most amazing and puzzling phenomena occurring in cloudland during the winter time is this, that the tiny cloud droplets, $\frac{1}{500}$ to $\frac{1}{3,000}$ of an inch in diameter, often retain their fluidity during zero weather, when greatly undercooled. More remarkable still is the discovery by the writer during recent years that there are times when these tiny fluid cloud droplets have, imbedded within them, solid crystalline nuclei of hexagonal form. (See fig. 1.). By correspondence with Prof. W. J. Humphreys and others, I have found that science as yet can offer no wholly satisfactory explanation of these phenomena.

In this connection it is of great interest to note that certain scalloped features that sometimes occur upon or within the faces of tabular snow crystals, greatly resemble the scalloped outlines of massive ice crystals when forming upon the surface of fluid water. They (the scallops) seem to indicate that fluid water once existed in the clouds upon such snow crystals.

Singularly enough, such scalloped features seem never to occur on both sides of a given crystal. They occur only upon certain restricted areas, encircling the plates, these areas presumably representing the region which was at one time immediately within their peripheral edges. But why a film of fluid water should form upon certain crystals only, and then only around their edges, and only upon one face, defies explanation unless we entertain the rather doubtful supposition that, for a time, two tabular crystals happened to arrange themselves in contact face to face and were later separated by wind or other action (collisions with other crystals). Scalloped features are shown in Figure 2. That tiny films of fluid water form easily upon certain facial areas of the tubular plates when their faces are in close contact with another tabular face seems proved from the fact that tiny microscopic scallops actually do sometimes form upon the under sides of tabular snow crystals resting upon a glass slide under a microscope. Those shown in Figure 3 actually formed before our eyes. In cases like this there is evidently a slight evaporation from the under side of the crystal, followed by condensation and crystallization, or else a slight surface (?) melting followed by crystallization.

Observation shows that in such cases the face of the tabular crystal is slightly frozen to the glass slide, presumably at the places where the scallops were. More amazing and much more puzzling is the occurrence of certain tiny dot-like features (systems of geometrically-arranged dots, presumably air bubbles) featured within some of the tabular crystals. Sometimes these dot systems have a marvellously symmetrical arrangement, as in Figure 4, picturing the central part of a crystal only, greatly magnified. They seem not always to be merely surface features (pits or indentations), as they sometimes resist evaporation like other deep-seated features (air bubbles).

In this connection it is instructive to note that lines of tiny air bubbles sometimes occur at the places of meeting and merging of the segments of a crystal. (See fig. 5). It is barely possible that these wonderful dotted systems are formed in this manner during the merging of segment to segment, or in some way while the processes of the filling in and encasement of the scalloped features, previously described, are accomplished.

(To face p. 530)

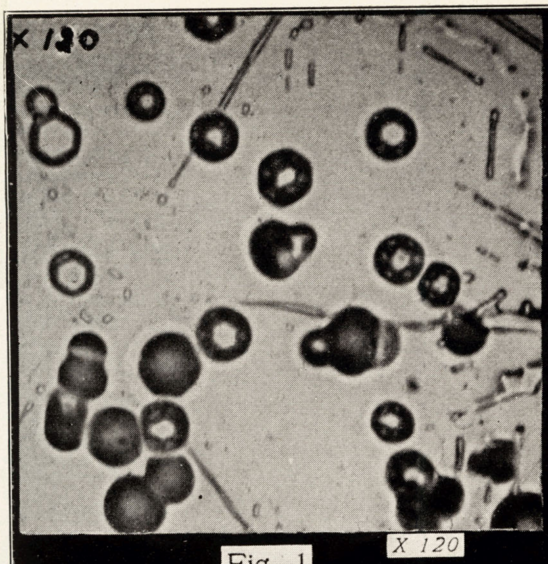


Fig. 1

Fig. 2

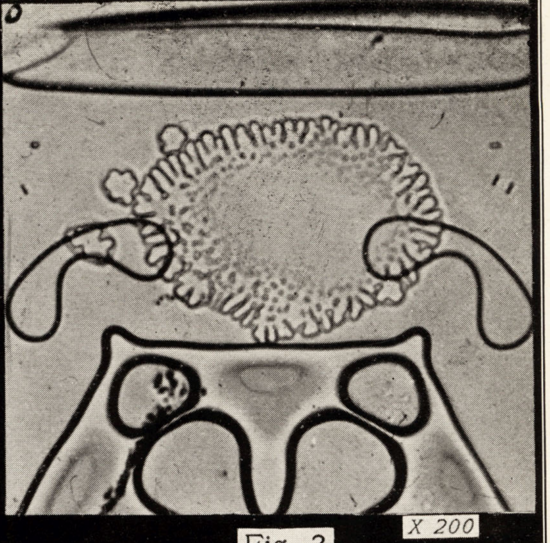


Fig. 3

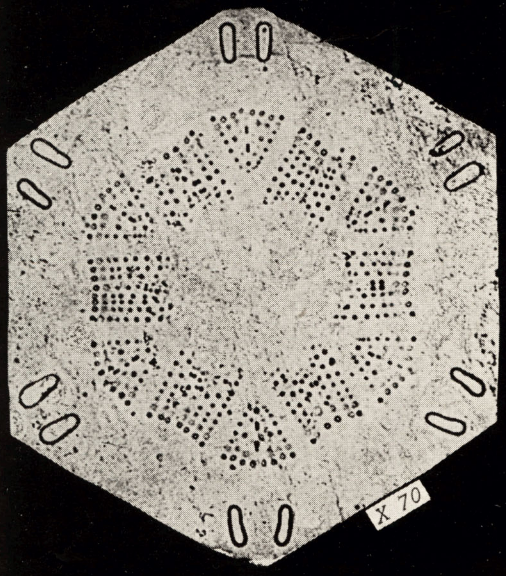


Fig. 4

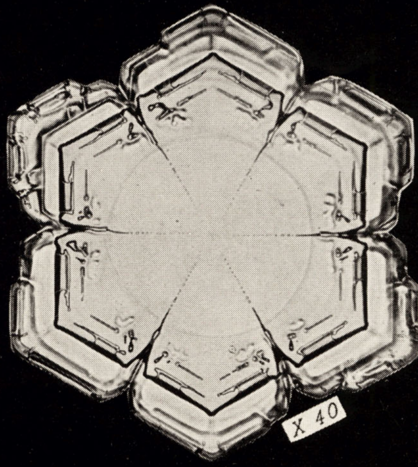


Fig. 5

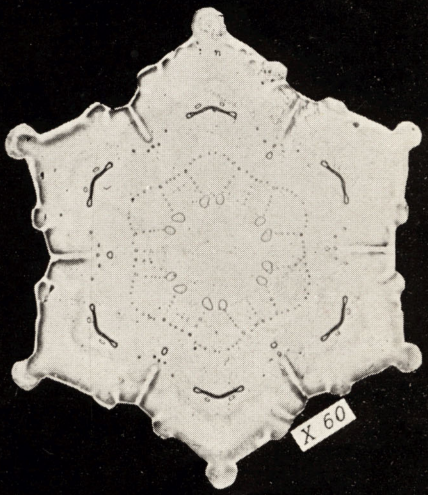


Fig. 6

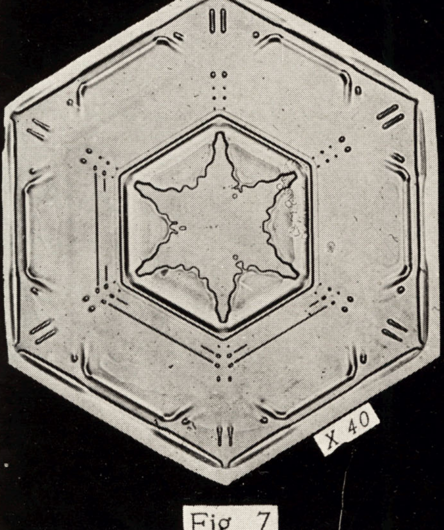


Fig. 7

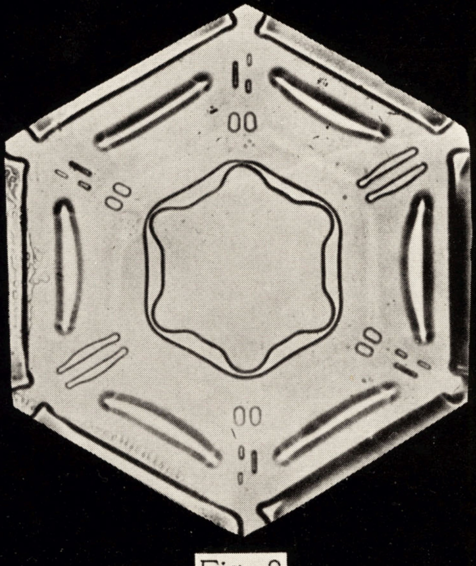


Fig. 8

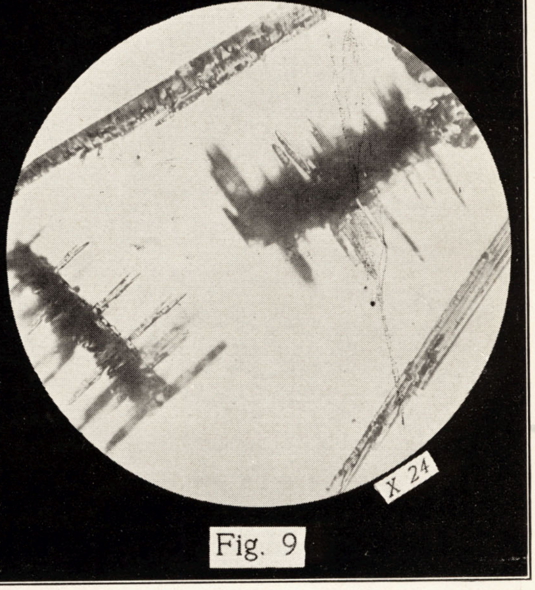


Fig. 9

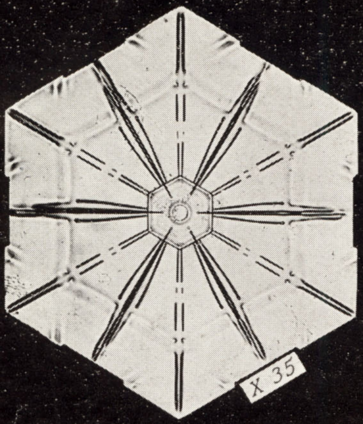


Fig. 10

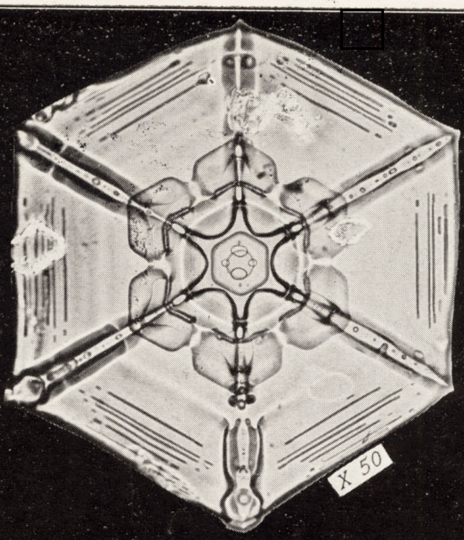


Fig. 11

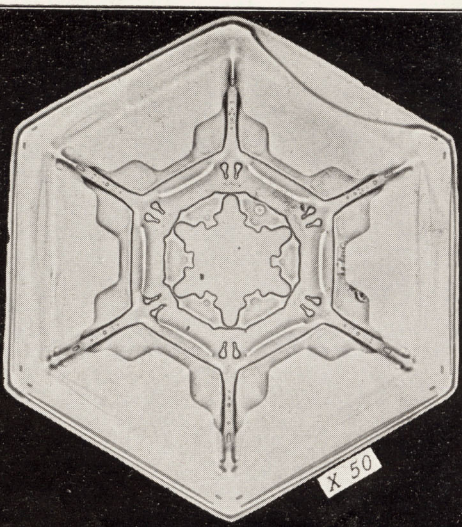


Fig. 12

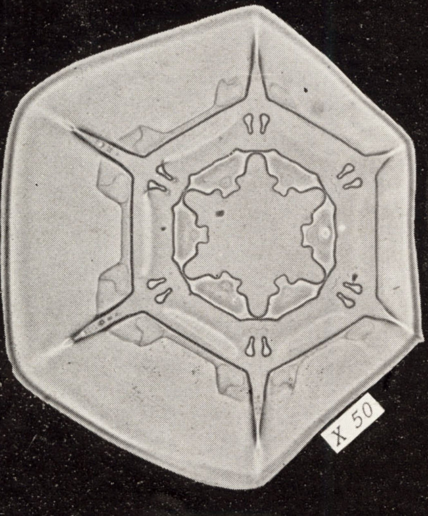
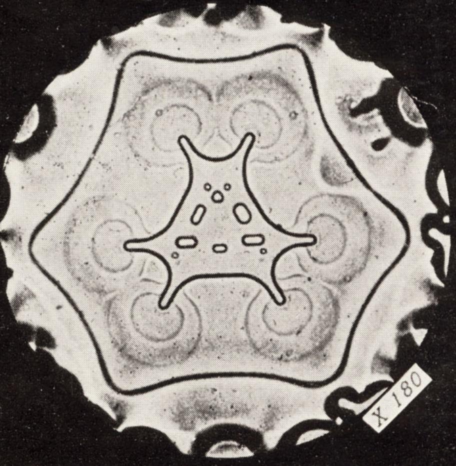


Fig. 13

Fig. 14



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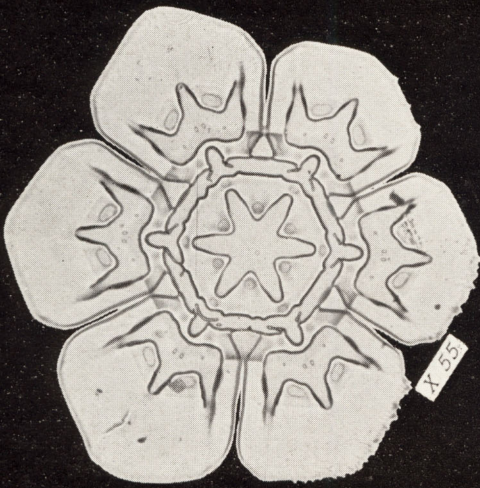

Fig. 16

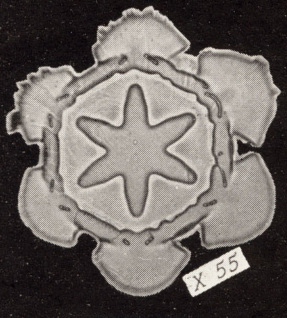

Fig. 17

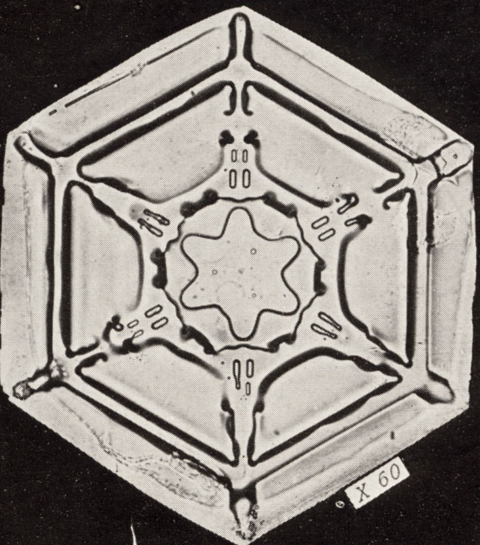

Fig. 18

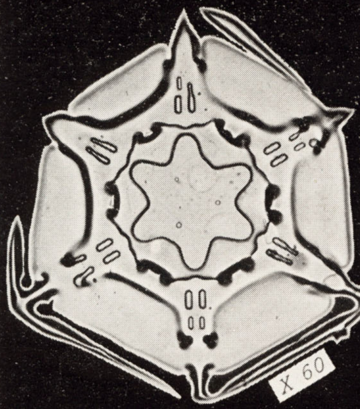

Fig. 19

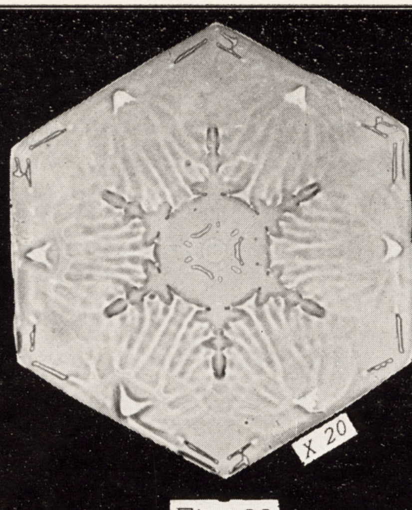

Fig. 20

Fig. 21

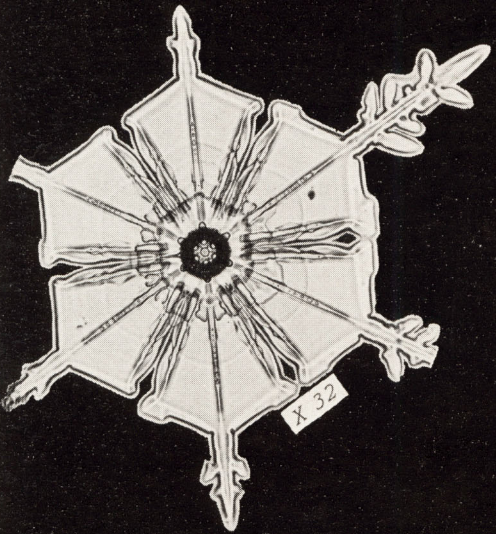

Fig. 22

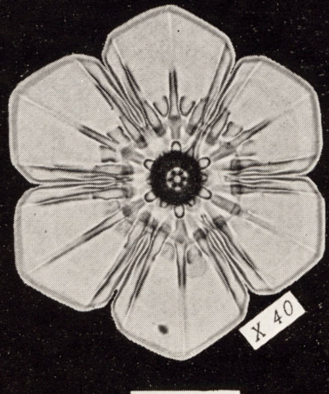

Fig. 23

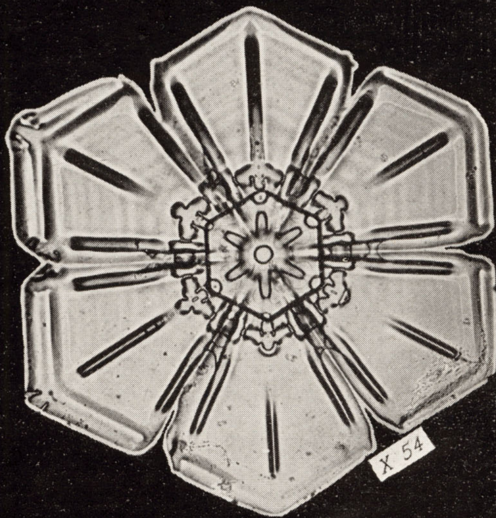

Fig. 24

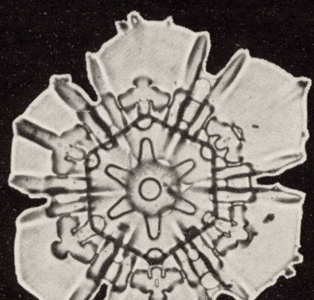

Fig. 25

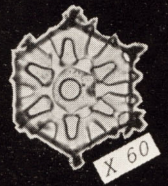

Fig. 26

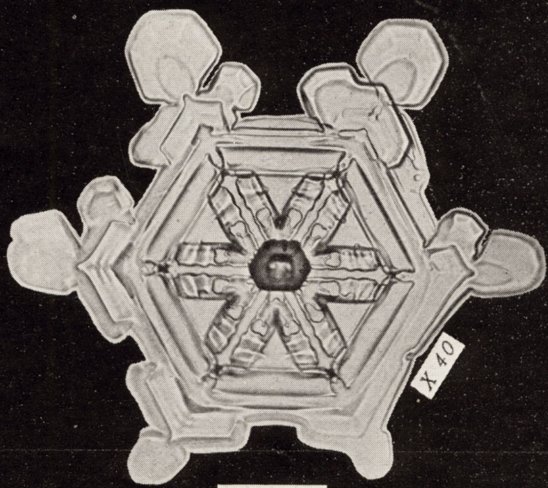

Fig. 27

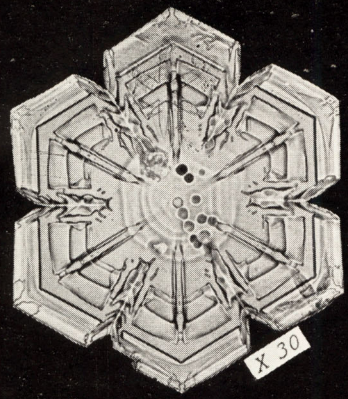

Fig. 28

Fig. 29

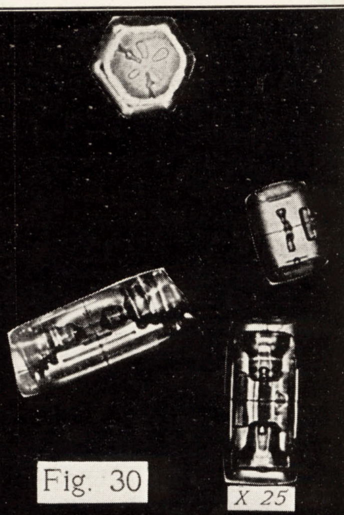

Fig. 30

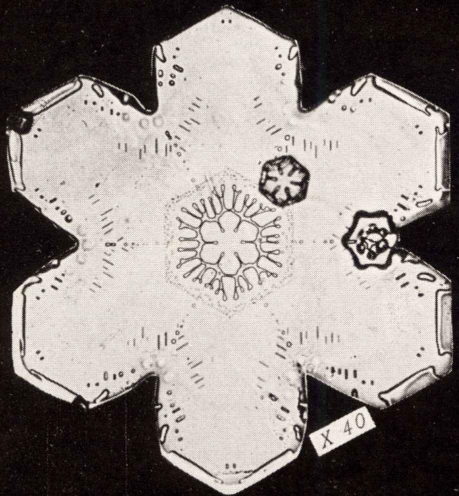

Fig. 31

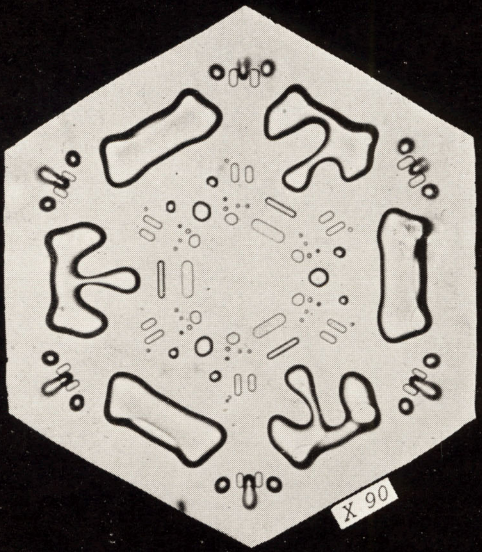

Fig. 32

Fig. 33

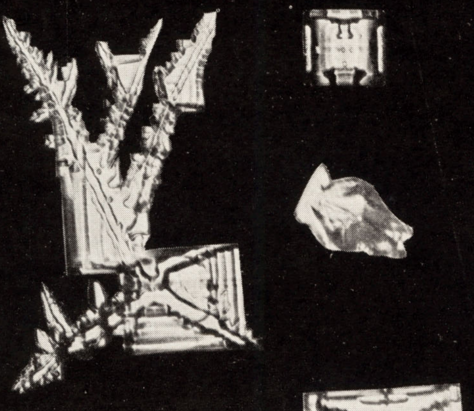

Fig. 34

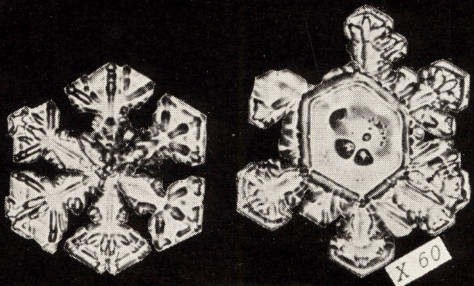

Fig. 35

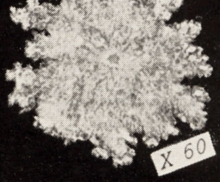

Fig. 36

In Figure 6 we see the skeletonized outline of a similar system of dots. Figure 7 possess features of especial interest. It will be noted that certain slender rod-like features, presumably air tubes, encircle the nucleus just half way around, and no further.

I have many other specimens exhibiting this interesting crystallographic habit. Some specimens show a marvellously perfect balancing of opposite parts, similar parts similarly modified. Figure 8 is a most interesting case in point.

Figure 9, in part a profile view of plate forms, is of interest because it shows the manner in which the needle-like additions, presumably acquired within the lower clouds, attach themselves in positions normal to its faces.

The modifications the crystals undergo as a result of progressive evaporation (evaporative erosion) has received my earnest attention during recent years. My series of photo-micrographs, picturing such phenomena is as yet inadequate, but will be augumented as opportunities permit. Evaporative erosion may be divided into two categories, facial, occurring upon their faces, and peripheral, occurring around their edges. Facial erosion tends to make tabular plates thinner, and to reduce the size and relief of any raised portion thereon. It also tends to deepen and enlarge any pits or indentations or sunken features extending beneath their faces.

Peripheral erosion progressively tears the crystals down around their edges, making the stars and plates progressively smaller, and rounding off the sharper angles and projections. Peripheral erosion tends to proceed fastest and to make indentations (notches) at all places where the stars or plates are thinnest. Conversely, it tends to proceed most slowly at all places having more than usual thickness or greatest refractability. Observers differ as to the character of many of the internal features, the lines, dots, shadings, etc., within them, and evaporative erosion helps to throw light upon the matter.

Some features are universally conceded to be minute inclusions of air (air tubes); others, to be the result of abrupt changes in thickness, or partial opacity. The origin and character of others, as for example the dark axial rays (usually double dark lines) that often radiate outward toward the corners of the hexagons, and some other features, are still somewhat in doubt.

Some observers assert the dark axial rays are hollow air tubes, hence lines of weakness. The writer has always been skeptical regarding this conception of them. He believes that if air is included it is in infinitesimal quantities, and that it is only such as is included alongside the outer sides of each of the long dark axial rays instead of centrally between them.

The behavior of these various features while undergoing evaporation is instructive.

Before considering this it may be well to consider the aspect of real air tubes in massive ice and show crystals. When these are viewed by transmitted light they usually present the appearance of two dark parallel lines. The snow crystal, Figure 10, contains typical examples of such air tubes. Returning to our consideration of the dark axial rays, a close study of them reveals that tiny air bubbles are often strung along their extent. Assuming these tiny air bubbles to be deep-seated, which seems likely from their persistence during evaporative erosion it is obvious that air tubes can not exist within air tubes. (See fig. 11.) This behavior while undergoing erosion seems also not favorable to the hollow-tube theory of them. For they are often so broad that, assuming them to be air tubes, they are relatively large compared to the tabular thickness of the plates (see again fig. 11), and should be lines of weakness and maximum erosion, unless we assume a marked thickening of the plates at their locality, i. e., raised icy ridges projecting above the normal tabular face or faces.

It is frequently the case as evaporation progresses that the outward ends of the axial rays do not evaporate as fast as the surrounding solid parts, and hence project slightly beyond them as though these ends were unusually resistant to erosion. Such was the case with the flake in Figure 11, and also with many other specimens. Evaporation, moreover, sometimes practically destroys the axial rays by means of facial erosion before peripheral erosion approaches the destroyed parts, which seems to indicate they are extremely raised features rather than internal ones. True deep-seated air tubes persist the longest of any of the features of snow crystals which are undergoing evaporation.

Figure 12 shows how the axial rays are in process of destruction by facial erosion before the near approach of peripheral erosion, also how it operates to lessen the breadth of such axial rays in just the manner it should, assuming them to be slightly raised ridges upon the tabular face.

In a previous article the writer showed how a slight variation in thickness of one side of a plate as compared with the opposite side caused evaporative deformation, and was one of the causes operating to destroy perfect natural symmetry. It frequently falsifies the image even before the skilled photographer can photograph it. A fracture operates in the same manner. In the case of the flake in Figure 12 the writer broke off a little from one edge of the plate while picking it up with the wooden splint used for this purpose. The crystal, as will be noted, was marvellously perfect and symmetrical. After a little, another picture of it was made (fig. 13). As will be noted, evaporation progressed with undue haste at and around the injured part, thus destroying the symmetry of the crystal and falsifying its image. This last plate is also instructive, as before noted, because the crystal had axial rays, and we see here again how facial evaporation reduced the breadth and distinctness of the axial rays, before the near approach of peripheral evaporation. As previously pointed out, while facial evaporation tends to reduce the size and relief of raised facial features, it would tend to enlarge and deepen sunken features, pits, bubbles, etc.

This may possibly explain the increase in the size and distinctness of the round circular figures shown just outside of the points of the nuclear star in Figures 14 and 15. It will be noted that the first exposure reveals but one circle at each star point, those being much smaller than the circles brought into view by the second exposure. The increase in the size and distinctness of some of the nuclear stars seen at the centers of certain snow crystals as evaporation proceeds is puzzling. (See Figs. 16 and 17.) May it be due to internal melting? Or must we conclude that such nuclear stars are also sometimes thinner than the surrounding parts, thus forming differences in star shapes? Figures 18 and 19 are of great interest in once again showing how the axial rays, and dark, encircling lines as well, are unusually resistant to evaporation.

Singularly enough, certain broad shadowy features sometimes occurring in crystals similar to those in Figure 20, quickly disappear through evaporation. (See Fig. 21.) The evaporative modifications which the flake in Figures 22 and 23 underwent are of much interest, as are the three evaporation stages shown in Figures 24, 25, and 26.

It is well known that tabular snow crystals, and especially branchy ones, rotate face downward while falling. As a result, growth material is supplied in undue proportions to one side only of each of the rays, producing abnormal growth thereon. A similar result is produced when one edge of a crystal is thicker than the opposite edge, causing it to fall steadily downward. Figure 27 is an instructive example of this kind.

The problem as to the nature of the nuclei around which snow crystals form is of much interest. If such nuclei are, as some assume, dust particles, they must be exceedingly small, invisible to ordinary microscopic vision, as none are found in my photomicrographs. That many of the crystals seize upon and crystallize around frozen cloud droplets seems very probable, as the nuclei of at least one half the crystals are tiny circular figures, looking much like an encased cloud droplet. Further support is given this theory by the fact that they correspond in size, also, with the cloud droplets.

Figure 28 pictures one of these circular nuclei, with some attached cloud droplets.

The columnar snow crystals, singularly enough, show no evidence of having crystallized around cloud droplets, as they do not possess circular nuclei. Some of them, like some plate forms, have perfectly limpid formless nuclei. But more often they possess one characteristic nuclear or central feature. This consists of a faint line across the column at their centers, normal to their greater diameter, seemingly bisecting the column in the manner shown in Figures 29 and 30. Growth from the ends downward and meeting at the center of the column might produce such an appearance, and offers a possible explanation. These specimens are interesting, moreover, because they show the so-called end cavities, which do not always meet at the center of the columns. A third flake of this series [not reproduced] has collections of granular cloud-droplet material upon one edge [side?—Ed.] only, proving that such columns descend in accordance with theory, i. e., in horizontal position and without rotating.

All keen and long-time students of the snow must have been often thrilled at the rare beauty and perfection of many of the tiny centerpieces possessed by numbers of the tabular crystals. Often otherwise imperfect specimens possess amazingly perfect nuclear parts. Many of these wonderful imitation gem-like centerpieces are almost unbelievably beautiful specimens of geometric art worthy of the skill of a master artist. Frequently the details pictured therein are too minute to be clearly shown with the ordinary magnification, or when the whole crystal is shown.

The writer has photographed during recent years many highly magnified centerpieces, with most interesting and most beautiful results. Such photographs, while not showing the crystals in the final or mature stages of growth, are yet true to nature, for they do picture them as they once were while yet in an immature, uncompleted state, in the clouds. And in a way, crystals are always in an immature state. We really never see a mature crystal, for, unlike vegetable and animal organizations, they will continue to grow indefinitely just as long as material is supplied them. Sometimes such immature forms become attached to "mature" crystals, thus preventing further growth, and are brought down unmodified to earth, as shown in Figure 31.

A study of these snow-crystal centerpieces shows that, in general, they are of the solid or quasi solid plate form. Space forbids the picturing of more than two of these, enlarged. One has been shown in Figure 4, the other is pictured in Figure 32, which is a marvel of quasi trigonal symmetry.

It has been a mooted question among scientists whether or not crystals forming under identical conditions would be identical in form. In the case of the snow crystals, for example, would all those originating in the given portion of a cloud be alike? Through a fortunate accident, the bursting of a water pipe, thereby flooding the floor of a cold room, one very cold night (25° F. below zero), the writer had the opportunity of observing water vapor crystallization under practically ideal, or nearly laboratory, conditions. Of course the conditions of humidity, air density, etc., were uniform within this room.[1] Upon entering the room in the morning, wisps of fog rising from the floor, and tiny crystals of hoar frost glittered from the wall and upon all objects, including my glass microscope slides. I at once realized the importance of the phenomenon and of securing photomicrographs of the crystals. Finding those on my microscope slides to be fairly typical of all in the room, I hastily made as large a series as possible. Although the heat of my body speedily arrested further growth of the crystals near me and soon caused evaporation to round off the sharp corners of the crystals upon my glass slides, by rushing in occasionally and making an exposure and then withdrawing for a while, I succeeded in my purpose. The tiny frost crystals, if such they may be called, attained a degree of perfection of form in this room such as I never saw elsewhere. The crystals, while mostly of the columnar and solid tabular forms, were not all of that character nor all alike. Some few assumed branching or quasi branching forms. Singularly enough, some of the plates grew in a quasi trigonal manner. Others developed in oblong plate form. It is probable that the branching forms, especially those with curving habits of growth, may have been a later phase of crystallization, and that they formed only after the air of the room became, in local regions, supersaturated with moisture. The curving, branchy forms are doubtless but quasi crystalline like similar frost crystallizations on windows. It is probable that groups of water molecules, rather than single ones, groups so large that as the molecules unite they come only partly under crystallographic law, unite to form such curving crystals. These appear to be cases of colloid crystallization.

Singularly enough, some of the tabular forms possessed tiny circular nuclei seemingly identical with those possessed by many of the snow crystals. Broad dark axial rays were present in some of the plate forms. It is interesting to note that many of the columnar forms had end cavities resembling those in similar snow crystals. Photomicrographs of many of these wonderful frost crystals are shown in Figures 33–36.

It would seem, from my observations in this case, that crystals forming under identical conditions will not be all alike. It seems evident that hexagonal, trigonal and oblong plate forms, six-petaled forms, and columnar forms, etc., will form side by side under identical conditions.

In concluding this brief sketch of snow crystal studies, the writer wishes once again to express his ever-growing amazement at the seemingly infinite variety and thrilling beauty of the tiny snow crystal gems. Many of my recent finds are, if possible, more beautiful than the earlier ones. New and beautiful designs seem to be as numerous now as when I began the work 40 years ago. While many of them are very similar one to another, I have, as yet, found no exact duplicates.

In this inexhaustible storehouse of crystal treasures, what a delight is in store for all future lovers of snowflakes and of the beautiful in nature.

[1] It may be questioned whether, since the floor was wet, diffusion of water vapor from this source would not maintain a somewhat higher humidity near the floor.—Ed.